Size-resolved particle distribution and gaseous concentrations by real-world road tunnel measurement

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Abstract: Measurements of aerosol particle number size distributions (15-700 nm), CO and NO_x were performed in a bus tunnel, Australia. Daily mean particle size distributions of mixed diesel/CNG (Compressed Natural Gas) buses traffic flow were determined in 4 consecutive measurement days. EFs (Emission Factors) of Particle size distribution of diesel buses and CNG buses were obtained by MLR (Multiple Linear Regression) methods, particle distributions of diesel buses and CNG buses were observed as single accumulation mode and nuclei-mode separately. Particle size distributions of mixed traffic flow were decomposed by two log-normal fitting curves for each 30 minutes interval mean scans, all the mix fleet PSD emission can be well fitted by the summation of two log-normal distribution curves, and these were composed of nuclei mode curve and accumulation curve, which were affirmed as the CNG buses and diesel buses PN emission curves respectively. Finally, particle size distributions of diesel buses and CNG buses were quantified by statistical whisker-box charts. For log-normal particle size distribution of diesel buses, accumulation mode diameters were 74.5～87.5nm, geometric standard deviations were 1.89～1.98. As to log-normal particle size distribution of CNG buses, nuclei-mode diameters were 21～24 nm, geometric standard deviations were 1.27～1.31.

Keyword: vehicle emission, particle size distribution (PSD), road tunnel, gaseous pollutants，mode diameter

Introduction

Traffic-related emissions contribute substantially to atmospheric particle concentration in many urban areas. These artificial airborne particulate matters (PM), consists of fine particles (<2.5μm) and ultra-fine particles (UFPs, <100 nm), are continually the major concerns for environmental and medical scientists due to their adverse health effects on human exposure, reduce visibility in urban atmosphere and their impact on climate change[1,2]. Nowadays, due to increasingly more stringent emission standards being introduced worldwide, vehicle control strategies based on engine design and after-treatment have effectively reduced the average particle mass emissions. However, these mass-resolving measures seem to have limited success in the reducing UFP numbers. Some studies have reported increased UFP numbers even after the introduction of treatment devices [3].

Although UFPs contribute very little to the total mass, they account over 80% of the total particle number in urban ambient air [4] and very often, over 90% in diesel vehicles [5]. The great numbers of these UFPs or nano-particles (<50nm) are suggested to be more relevant to human health effects than the particle mass [6~8]. In this regard, the determination of the numbers and sizes of small nano-particles is becoming more significant in terms of environmental health effects. There is a need to characterize the nature of vehicle particle emissions, as there is now more advanced particle sizing instrumentations are widely available in the market to open up the possibility for measurements.

A number of studies have examined the size-resolved and transient nature of motor vehicle particle emissions. Signature size distributions for light duty diesel and gasoline engine exhaust particulate matter were determined by dynamometer tests under different driving cycles and loads [9]. Ristovski (1998)[10] and Maricq (2001)[11] observed a nearly single log-normal size distribution of exhaust particles from gasoline-powered and liquefied petroleum (LPG)-powered passenger vehicles of which the median diameters of particles were in the size range of 40~80 nm, basically in accumulation mode. Maricq (2001)[3] and Ristovski (2006)[5] reported single log-normal or bimodal log-normal shapes particle size distribution emitted from diesel buses and diesel light-duty vehicles in the range accumulation mode, sometimes with a nuclei-mode (median diameter smaller than 50 nm). Jayaratne et al. (2009)[12] suggested a single log-normal shape particle emissions from CNG (Compressed Natural Gas) buses which are in the nuclei mode, and the median particle mass emission factor from the CNG buses was less than 1% of that from the diesel buses at all loads. From these studies above, total particle exhaust number concentrations are different in orders for various kinds of vehicles or even in different operation modes, however, the particle size distribution curves of all vehicles exhibit single mode or bimodal log-normal profiles, whether the vehicles use lead or unleaded gasoline fuel for Light Duty Vehicles (LDV), or use low sulphur (LD) or ultra-low sulphur (ULD) diesel fuel for Heavy Duty Vehicles (HDV), or even with or without using after-treatment and catalytic converters for vehicles.

So far, extensive real-world studies have been mainly focused on size-resolved emission factors (EFs) for particle number, particle mass and other gaseous pollutants. Zhu et al. (2002)[13] and Mejia et al.(2008)[14] characterized ambient UFPs profiles in open field highway experiments under different distance to the vehicle exhaust and various wind direction. Likewise, tunnel studies, being closer to ambient conditions than a dynamometer test while allowing for average emissions measurements over large samples of vehicle fleets, have been conducted as a better real world measurement approach to determine particle number emission factors (EFs) under various driving conditions [15~19].

As there are limit knowledge of size-resolved signature of vehicle particle emissions based on real world measurement, this study seeks to characterize the Particle Size Distributions (PSDs) of on-road diesel buses and CNG buses by using log-normal curve fittings of Scanning Mobility Particle Sizer (SMPS) field measurement results monitored in a road tunnel in Australia. The purpose of this work is to develop a mechanistic particle number emission model for determination of EFs from mobile sources. Total particle number concentrations, gaseous pollutants of NO_x and CO concentrations were also investigated by this work during the 4 consecutive days' measurement.

Methodology

Tunnel description

Sample collection was performed in the Vulture Street tunnel of Brisbane, Australia from 17 June (Friday) to 20 June (Monday) 2005. As one section of Bus Rapid Transit (BRT) in the downtown, the 511m length tunnel connects two bus stations and is used exclusively for buses passing through. The tunnel is approximately flat in the covered portions except with slightly curved descending and ascending sections at both portals. The single-tube tunnel has a cross-sectional area of around 60 m^2 for bi-directional traffic flow with one lane in each direction. A vehicle speed limit of 50 km/h is imposed in this tunnel, and all buses keep to this cruise speed in normal condition. Three sets of triple-axial-fan units are equipped along the tunnel which operates to keep a positive air flow from Mater portal (intake) to Southbank portal (exhaust). Air speed in the tunnel is recorded by an ultrasonic sensor in the mid tunnel which is installed on the inside top roof of the tunnel. As Fig.1 shows, two sample sites were selected for pollutants measurement. One site was near air-intake portal (S1), the other site located in the middle of the tunnel (S2).

Bus fleet

Traffic flow through the tunnel consists of diesel buses which fuelled with ultralow sulphur diesel (ULS: 50ppm and CNG buses which fuelled with compressed natural gas. Bus fleet travelled through the tunnel were monitored at the Southbank Bus station (S3) by four sensor-recorder systems, two in the inbound (towards Southbank) lane and two in the outbound (towards Mater Portal) lane. All sensors would register the identity number of each bus which can be used to recognize bus fleet composition.

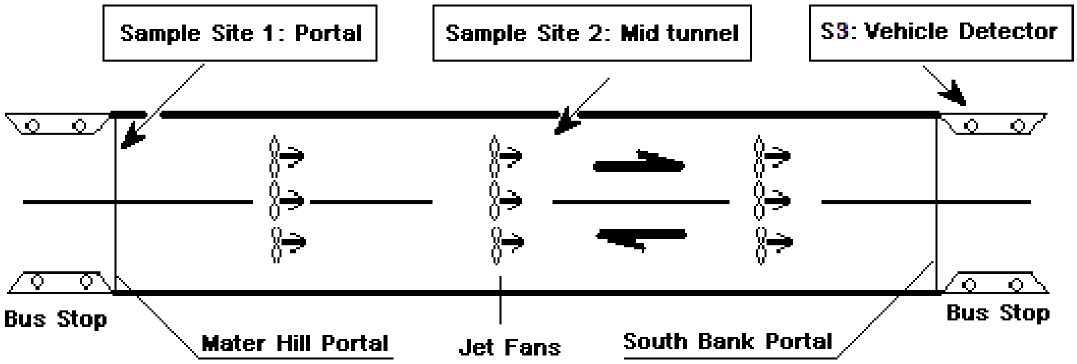


Fig. 1 Profile of the Vulture Street Tunnel and location of sample sites

Instrumentation and Calibration

The main objective of measurements was to evaluate the emission freshly exhausted from buses in the mid tunnel, in order to do this, two sets of continuous analyser instruments were used in the sample sites, both in the portal (S1) and middle of the tunnel (S2). As a consequence, time series of particle and gaseous pollutants parameters could be obtained synchronously. Two Scanning Mobility Particle Sizer (SMPS, model 3934) were in operation to measure the particle size distribution (PSD) with diameters between 15~700nm with 106 size bins. The components of both SMPS system consisted of the same type and model, a 3071 TSI electrostatic classifier and a Condensation Particle Counter (CPC 3010). The flow rates were set to 0.5 and 5 L/min for the aerosol and sheath flow respectively, and the scanning times were 120s and 30s respectively. Particle number concentrations were measured with two TSI CPCs, model 3022A, a response time of 1s. The detection range from 7nm to 3 µm and an upper concentration level of 10^7 particles per cm^3. NO_x and CO concentration were monitored, which were logged at time intervals of 1 mins. A summary of the main instrumentation is presented in Table 1.

All instruments were tested and calibrated in the International Laboratory of Air Quality and Health (ILAQH) of Queensland University of Technology (QUT), prior to transfer to the measurement site. Particle loss of the sampling tubes for the instrumentation were negligible, as previously, measurements in the laboratory found particle sample loss in a 10 metres long conductive silicone tubing was less than 1%.

Table 1. Instrumentation

Parameter	Measurement (method/instrument)	Time Interval	Sampling sites
Air flow (m/s)	DURAG D-FL 200T	1 min	S1
Traffic flow	4 Sensor recorder systems	1 min	S3
Particle size distribution	SMPS 15-700nm (Model 3071 with CPC 3010)	2.5 mins	S1,S2
Total particle number concentration	CPC TSI 3022A (7-3000nm)	1s	S1,S2
CO (ppm)	TEI Model 49C	1 min	S1
NO_X, NO (ppb)	Ecotech ML9841; TEI Model	1 min	S1;S2

SMPS: Scanning Mobility Particle Sizer™;

CPCs: Condensation Particle Counters.

Data analysis

Previous field studies and laboratory experiments have indicated two distinct dilution stages of exhaust nano-particles emitted from the tailpipe [20]. The first 'tailpipe-to-road' process may be very fast and strong, which would only take 1~5s. During the second 'road-to-ambient' stage, the plume was further diluted by a factor of 10 in 3~10 mins. As all exhaust particles passed through the whole tunnel in less than 3 mins during the measuring period, the size-segregated particle number emission factors (EFs) of all 15~700nm size bins can be calculated by a number balance equation in this work.

The combined particle number, EFs, of mixed bus fleet (per km travelled) can be determined by using Eq. (1):

$$EF_{c,i}(t) = \frac{[C_{2,i}(t) - C_{1,i}(t)]AV(t)}{N(t)L} \qquad (1)$$

where $C_{1,i}$ and $C_{2,i}$ are particle number concentration measured at the mid tunnel and entrance of i diameter size range, respectively; V is the mean value of air velocity in the tunnel; A is the tunnel's cross-section area (60 m^2); L is the distance between the points of measurement, S1 and S2 (255 m); t is time segment taken to particles sampling and in this study was 30-mins.

Since the traffic flow of diesel buses and CNG buses can by identified by the traffic sensor systems, particle number, EFs, of diesel bus and CNG can be derived by multi linear regress method as given by Eq. (2):

$$EF_{c,i} = \frac{n_D}{n_D + n_{CNG}} EF_{D,i} + \frac{n_{CNG}}{n_D + n_{CNG}} EF_{CNG,i} \qquad (2)$$

where $EF_{D,i}$, $EF_{CNG,i}$ are particle number emission factors of diesel buses and CNG buses; n_D and n_{CNG} are traffic flow rate of diesel/CNG buses, respectively.

In this work, a multi log-normal distribution function was used to parameterize the mixed diesel/CNG buses emission particle size distributions, as defined by Eq. (3):

$$F(D_p, \overline{D}_{p,i}, N_i, \sigma_i) = \sum_{i=1}^{n} \frac{N_i}{\sqrt{2\pi}\log(\sigma_i)} \times \exp\left[-\frac{[\log(D_p) - \log(\overline{D}_{p,i})]^2}{2\log^2(\sigma_i)}\right] \qquad (3)$$

where D_p is the diameter of an aerosol particle. Three parameters characterize an individual log-normal mode i: the mode number concentration N_i, geometric standard variance σ_i, and geometric mean diameter $\overline{D}_{p,i}$. The number of individual log-normal modes that characterize the particle size distribution is denoted by n, which were 2 in this work.

Results

Traffic Flow Rate.

Fig.2 displays the traffic flow rate of mixed bus fleet on Monday 20 June 2005, with time interval of 30 minutes in the tunnel. The diesel buses flow rate was also recorded correspondingly. The traffic flow was with a two-peak mode, the peak traffic hours were 7:30-9:30 in the morning and 16:30- 18:30 in the evening. It is a typical diurnal traffic pattern of weekdays as all buses implement approximately identical time table through the tunnel. The traffic density on weekdays is about 2,100 per day, 56% are ULS diesel buses and the others are CNG buses. Diesel bus fractions range between 0.4~0.7 in each 30 mins time intervals. On weekends, the traffic densities are approximately 50% on Saturday and 65% on Sunday respectively to the weekdays.

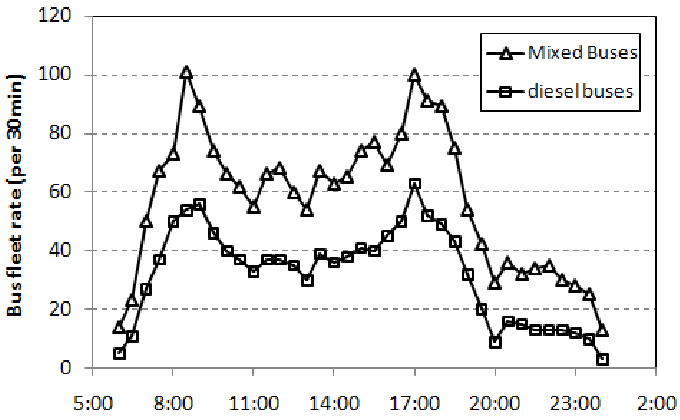


Fig.2 Typical weekday traffic flow (Monday, 20 June 2005)

Air Flow Rate.

Time series of air flow velocity of four measurement days is illustrated in Fig.3. On Friday and Sunday, the air velocity in the tunnel fluctuated greatly in the range of 0~3 m/s. It implies that when the natural wind flow is opposite to the main air stream with varied intensity, axial fans in the tunnel would be trigged to operate frequently to transform a positive air flow. As a result, it appears a strong pulsation shape air flow in the tunnel. Under this scenario the airflow would be regarded as natural mode. The mean air speeds are 1.7±0.6 (STD) m/s on Friday and 1.35±0.79 m/s on Sunday. On Saturday and Monday, the axial fans were operated compulsively to form a longitudinal air flow, in this mode the air flow would be relatively stable, the average speeds would sustain at 2.15±0.34m/s and 3.87±0.29 m/s respectively.

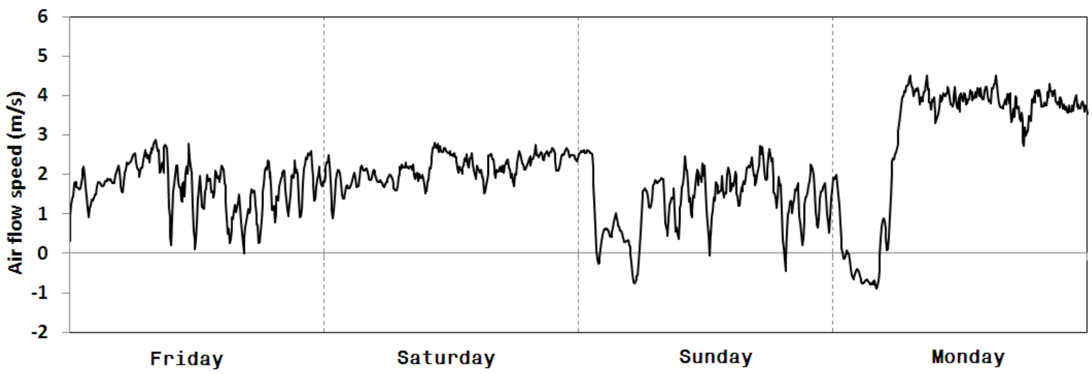
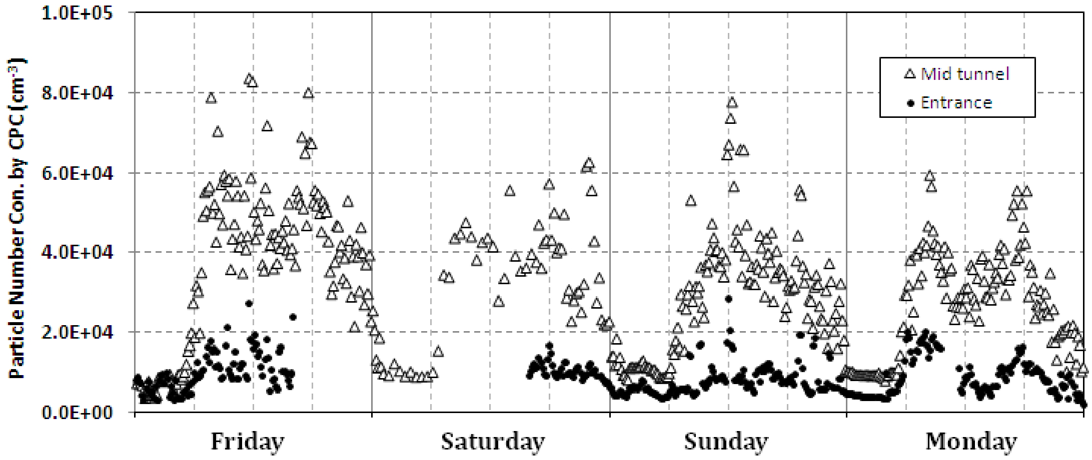


Fig.3 Air Flow Velocity



Note: The entrance particle number concentration data from Friday noon to Saturday noon was lost due to the instrument failure.

Fig.4 Total particle concentration by CPC

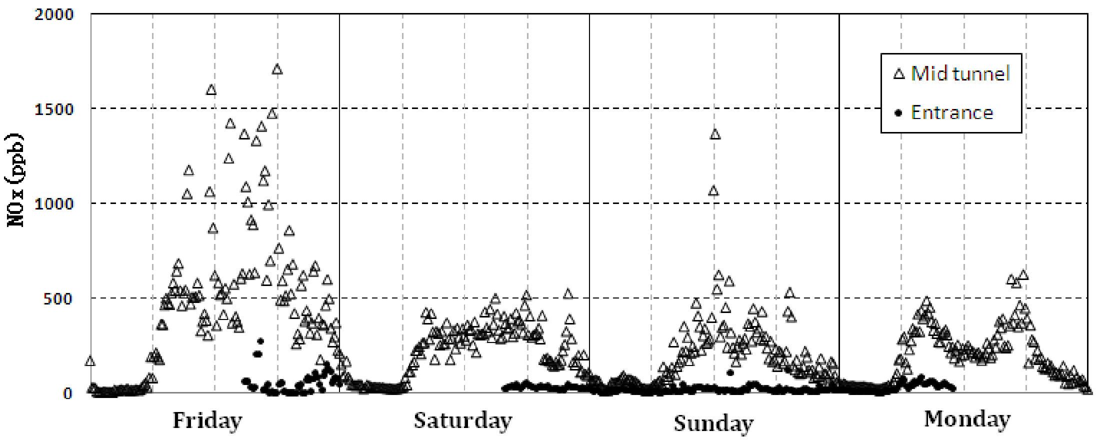


Fig.5 Time series of NO_x, Friday 17 to Monday 20 June 2013

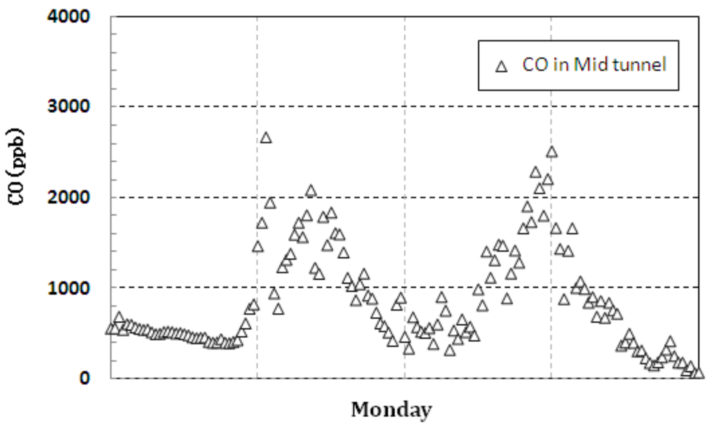


Fig.6 Time seires of CO on Monday, 20 June 2005

Total particle number (TPN) concentration

Diurnal time series of TPN concentration in the mid tunnel and at the tunnel entrance are presented in Fig.4. On Friday 17 June 2005, under natural air flow mode in the mid tunnel, TPN of morning peak was 5.65×10^4cm^{-3} (s.d.=9.57×10^3cm^{-3}) between 7:30 and 9:30. The evening peak was 5.91×10^4 cm^{-3} (s.d.=9.66×10^3cm^{-3}) between 16:30 and 18:30. Daily average of TPN was 4.82×10^4cm^{-3} (s.d.=1.22×10^4cm^{-3})

from 6:00 to 22:00. As to TPN under longitudinal mode on Monday 20 June 2005, with mean air speed of 3.9 m/s, TPN of the morning peak was 4.33×10^4 cm^{-3} (s.d.=$7.5\times10^3 cm^{-3}$) and evening peak was 4.42×10^4 cm^{-3} (s.d.=$8.5\times10^3 cm^{-3}$). Daily average of TPN was 3.38×10^4 cm^{-3} (s.d.=$9.2\times10^3 cm^{-3}$). Daily averaged TPN on Saturday 18 June 2005 and on Sunday 19 June 2005 were: $3.92\times10^4 cm^{-3}$(s.d.=$1.11\times10^4 cm^{-3}$) and $3.54\times10^4 cm^{-3}$ (s.d.=1.27×10^4 cm^{-3}) respectively.

Diurnal variation of TPN at the entrance was approximately as the same trend as with the TPN variation in the mid tunnel; this is illustrated more clearly by the Monday results under longitudinal flow mode. This could be due to the influence of Bus station, which is only 15 metres away from the entrance portal; pollutants could be induced to flow into the tunnel by bus traffics or sucked in by the axial fans in the tunnel. The two peaks TPN were 1.71×10^4 cm^{-3} (s.d.=$1.7\times10^3 cm^{-3}$) and 1.28×10^4 cm^{-3} (s.d.=$2.1\times10^3 cm^{-3}$) on Monday morning and evening, the daily average was 1.07×10^4 cm^{-3} (s.d.=$4.6\times10^3 cm^{-3}$) on that day. Average TPN in the mid tunnel from 2:00 to 5:00 each day was 7.5×10^3 cm^{-3} (s.d.=$2.7\times10^3 cm^{-3}$), when no bus pass through at that time.

NO_x and CO

NO_x and CO diurnal concentration patterns in the mid tunnel (Fig.5, Fig.6) have similar daily trend as traffic flow rate, although CO concentration was only monitored on Monday 20 June 2005. "M" shape daily concentrations were observed both for NO_x and CO on each weekday. Daily average concentration of NO_x on Friday 18 June 2005, was 705ppb, which was 2.6 times higher than that measured on Monday 20 June 2005. CO daily average concentration was 265ppb on Monday, 20 June 2005.

Daily average particle size distribution (PSD)

In order to evaluate the details of particle emission from traffic fleet source, particle size distribution was measured by SMPS both at the tunnel entrance and in the mid tunnel, each SMPS scan took 2.5 minutes. 4 consecutive days SMPS data results were obtained, providing the daily average profile of particle size distribution which should be viable. Fig.7 presents daily averaged SMPS differential particle concentration data from 6:00 to 22:00 of each day. These were computed by taking the arithmetic sum of the differential concentration values in each size bin and dividing by the number of contributing SMPS scans.

As is shown in Fig.7, all the daily averaged PSD at the tunnel entrance in 4 days were taken as with identical uni-modal accumulation modes. The mode diameter peaked within the 53 to 89 nm range. CMD (Count Median Diameter) was also used to represent particle size and trends in size distribution, which similarly range between 61 to 89 nm. The integrated concentrations ranged from, 5,600 cm^{-3} to 8,250 cm^{-3}. The profiles of PSD in 4 days at the entrance were similarly lognormal, and were assumed to be due to the effect of ambient background aerosol and traffic emission of the nearby bus station, which is situated about 15m distance to the entrance portal. A summary of the SMPS scans obtained at the tunnel entrance is shown in Table 2.

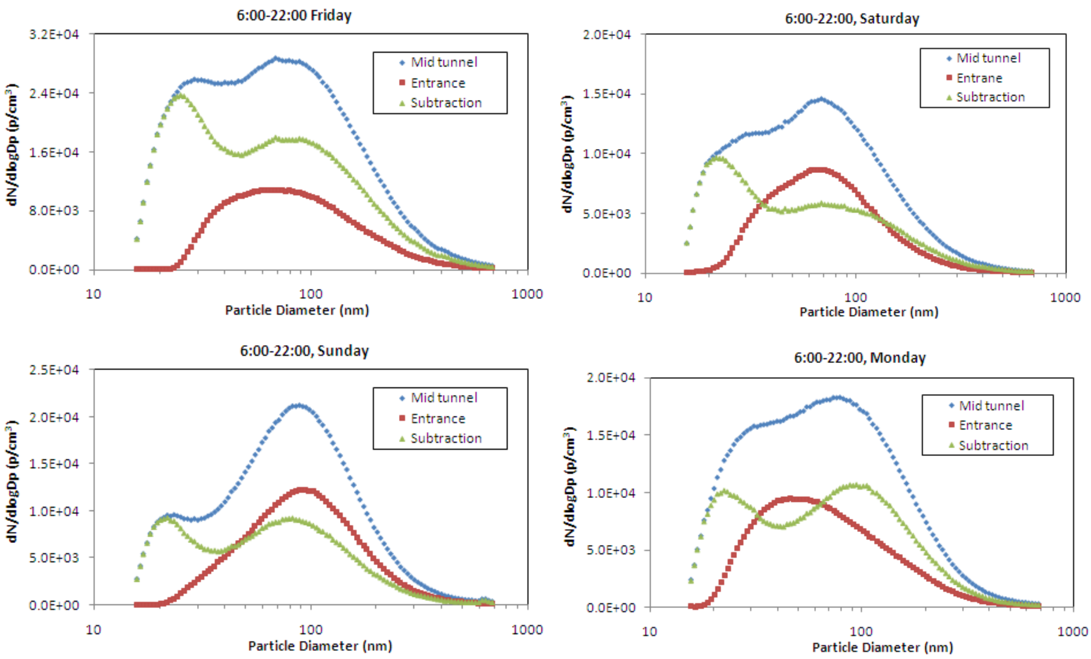


Fig 7. Daily averaged SMPS scan results (17 – 20 June 2005)

According to the 4 days average results, daily averaged PSD in the mid tunnel each day as shown in Fig.7can be regarded as with bimodal modes. One mode peak diameters were in nuclei mode, ranged from 22 to 28 nm, another peaks were in accumulation mode, which ranged between 66 to 86nm. Daily CMD ranged between 60 to 75nm, which would be near to each day accumulation mode diameters. The averaged integrated concentration on Monday (20 June 2005) was 17,090 cm^{-3}, which was 1.65 times lower than the corresponding result on Sunday 19 June 2005, due to the effective longitudinal ventilation in the tunnel on Monday. The integrated concentrations in the mid tunnel during weekends (Saturday and Sunday 18-19 June 2005) were 1.75~2.2 times lower than the concentrations on Friday (17 June 2005) due to the smaller traffic flow rate during weekends. Table 3 presents the summary of PSD in the mid tunnel.

Table 2 Daily SMPS data at tunnel entrance (17-20 June 2005)

SMPS Scan date (2005)	Scan numbers	CMD (nm)	mode D (nm)	Integrated conc. (cm^{-3})
Friday	384	76.5	68.5	8,245
Saturday	357	66.8	64	5,615
Sunday	384	88.6	89	7,777
Monday	376	60.6	53.3	7,118

Table 3 Daily SMPS data at the mid tunnel (17-20 June 2005)

SMPS Scan date (2005)	Scan numbers	CMD (nm)	mode 1 D (nm)	mode 2 D (nm)	Integrated conc. (cm^{-3})
Friday	384	62.9	27.9	80	28,248

Saturday	379	58.9	22.5	66.1	12,591
Sunday	384	75.4	22	86	16,120
Monday	384	62.9	27	81	17,085

Daily average SMPS results in the mid tunnel and at the entrance exhibit different modal modes. The uni-modal aerosol PSD at the entrance was assumed to be composed of ambient urban background particles and diluted emission particles from buses, as the bus station is near the entrance portal of the tunnel. For the sake of identify aerosol emission contribution of traffic flow in the tunnel, daily averaged PSD in the mid tunnel was subtracted by the corresponding data at the entrance, the subtraction curves are also presented in Fig.7. All the 4 corrected averaged PSD curves have distinct bimodal profiles, the nuclei modes of 4 subtraction curves ranged between 21 to 24nm, the accumulation modes ranged between 80 to 91.5nm. As these daily subtraction curves are all seen alike the combination effects of two log-normal curves in different modes, therefore the mixing traffic-sourced PSD could be fitted by two single log-normal mode curves.

Size resolved particle number EFs

According to monitoring data of the 4 days, as on Monday (20, June) the tunnel wind speed is stronger and relatively stable, and also with a typical traffic flow rate, we choose Monday data from 6:00am to 10 pm to compute size resolved particle number (PN) emission factors (EFs) of the mix vehicles fleet, diesel buses and CNG buses by MLR method with a time interval of 10 mins, the calculation results is as Table 4.

Table 4. Size-Resolved PN Emission Factors of Mix fleet, Diesel and CNG bus (p/veh.km)

Diameter range （nm）		15-25	25-41	41-65	65-104	104-166	166-264	264-421	421-700	Total size
Mixed fleet	mean	4.52E+13	4.15E+13	4.09E+13	5.38E+13	4.67E+13	2.37E+13	7.63E+12	2.14E+12	2.61E+14
	s.d.	3.06E+13	3.03E+13	2.42E+13	2.59E+13	2.70E+13	1.60E+13	6.45E+12	2.05E+12	1.18E+14
Diesel bus	mena	3.46E+13	5.31E+13	6.72E+13	8.40E+13	8.52E+13	5.06E+13	1.69E+13	4.46E+12	3.96E+14
	s.d.	1.37E+13	1.36E+13	1.05E+13	1.11E+13	1.14E+13	6.55E+12	2.72E+12	8.86E+11	5.11E+13
CNG bus	mean	5.84E+13	2.69E+13	8.00E+12	1.61E+13	-1.42E+12	-9.93E+12	-3.94E+12	-7.51E+11	9.33E+13
	s.d.	1.70E+13	1.68E+13	1.30E+13	1.38E+13	1.41E+13	8.10E+12	3.36E+12	1.10E+12	6.32E+13

As Table 4 shows, the total particle number EFs (15~700nm) emitted from the mixed fleet was 2.61E+14 p/veh.km. Comparatively, Jamriska [17]derived a very close result of 3.11±2.41E+14 km^{-1} in the same tunnel measured in 2001. Geller [18]obtained 2.73±0.83E+15 km^{-1} (derived from PN per kg) for HDV which particle size ranges in 7~270nm. Imof [19] calculated 3.94 E+14 km^{-1} in Plabutsch tunnel and 6.84+14 km^{-1} in Kingsway tunnel for HDV by SMPS(15-700nm). Kristensson[15] measured 4.6±1.9E+14 km^{-1}(3~900nm) for mixed LDV and HDV traffic flow. Abu-Allaban[16] derived 2.6 E+14 for HDV ranges in 1~400nm in Tuscarora tunnel. Total PN EFs in this study shows no striking difference to the former real world measurements.

Furthermore, total PN EFs of diesel buses and CNG buses were 3.96E+14 p/veh.km and 9.33E+13 p/veh.km correspondingly, and the ratio was about 4 times as diesel bus PN emission level to that of CNG bus emissions. For the analysis of particulate emission levels of different particle sizes, 8 size ranges PN EFs according to the logarithmic average particle size are also provided in, Table 4. As can be seen, diesel buses emitted particles mainly in 41-65 nm, 65-104 nm, 104-166 nm size section(accumulation mode), emission factors were 6.72E+13, 8.4E+13, 8.52E+13 p/veh.km. CNG buses released smaller particles, mainly in the 15- 25 nm, and 25-41nm (nuclei-mode), emission factors were 5.84E+13, 2.69E+13 p/veh.km respectively. For *Dp* greater than 100 nm, CNG PN EFs negative values would be regarded as MLR calculation error, as CNG buses mainly emit nuclei-mode particles, >100 nm diameter particles number emission would be ignored.

Fitting curve of 30 minutes averaged subtraction SMPS scans

In order to confirm the notion above, two-lognormal curves were used to fit the traffic fleet sourced curves, which were the averaged subtraction SMPS scans between PSD data in the mid tunnel and the corresponding data at the entrance measured at every 30 minutes during the monitoring period of 17 – 20 June 2005.

The multi- lognormal distribution fitting function *F* was determined mathematically using Eq. (3).

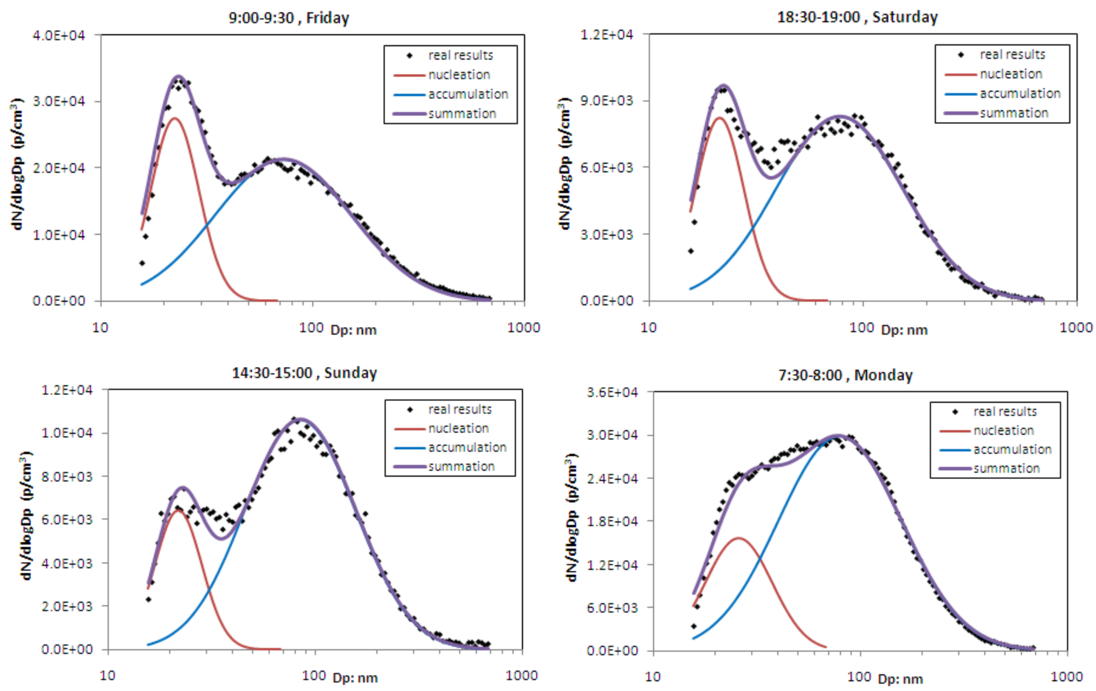


Fig.8 Typical Log-normal fitting curve of the subtraction PSD

In order to confirm whether the mode diameter and σ values of each decomposed log-normal curve serves the same discipline, a large number of curves were fitted based on the 30 minutes averaged corrected SMPS results (mid tunnel data subtract entrance data) from 6:00 to 22:00 of 4 days, totally 90 fitting curves were obtained. All the averaged subtraction PSD can be well fitted by the summation of two log-normal distribution curves, and these were composed of nuclei mode curve and accumulation curve respectively. The correlation coefficients between combined fitting curves and corresponding in-situ scans for totally 90 fitting scans were 0.972 to 0.998. Fig.8 displays 4 cases of typical fitting results of the 4 measurements days in different time range respectively. As is shown in Fig.8, each composition curve is the summation of two lognormal curves, which are composed by the nuclei mode and accumulation mode PSD curve separately. The composition of the fitting curve is closely matched with the real mixed buses sourced emission data with the correlation coefficient larger than 0.985. Details of the parameters of these 4 cases are presented in Table 5.

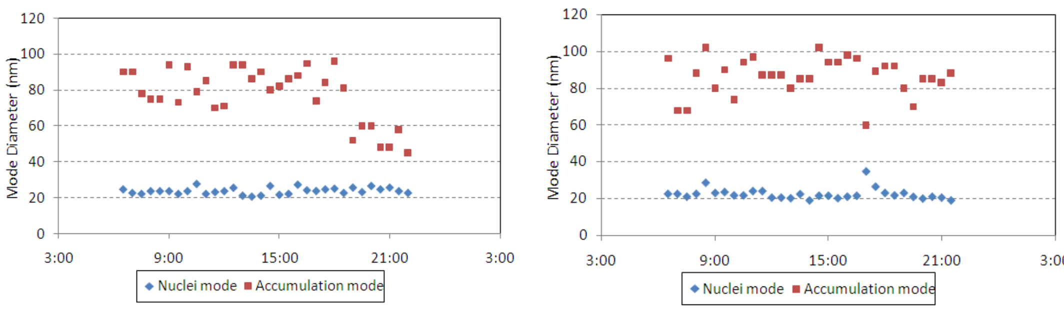
Compare to the decomposed log-normal PSD curves of 4 cases, under nuclei mode, although the differential mode diameter number concentration N_i varied greatly from 5.60E+03 to 2.75E+04 cm^{-3}, however, the mode peak diameters $\bar{D}_{p,i}$ were very close and ranged between 21.5 to 26nm, with the standard variance σ_i ranged between 1.3 to 1.35. The decomposed log-normal PSD curves under accumulation mode also exhibited similar discipline, the differential mode diameter number concentration N_i varied from 6.26E+03 to 2.13E+04 cm^{-3}, mode peak diameters $\bar{D}_{p,i}$ were mostly similar and ranged between 73 to 80nm, with the standard variance σ_i similarly ranged between 1.9 to 2.1.

Table 5 Log-normal parameters of the typical fitting PSD curves

Day	Time	Nuclei mode			Accumulation mode			Correlation
		D1	σ1	N1	D2	σ2	N2	Coeff.
Fri.	9:00-9:30	22.5	1.3	2.75E+04	73	2.1	2.13E+04	0.9896
Sat.	18:30-19:00	21.5	1.3	5.60E+03	78	1.98	6.26E+03	0.9861
Sun.	14:30-15:00	23	1.3	6.17E+03	80	1.9	1.06E+04	0.9913
Mon.	19:00-19:30	26	1.35	4.57E+03	80	1.98	6.70E+03	0.9899

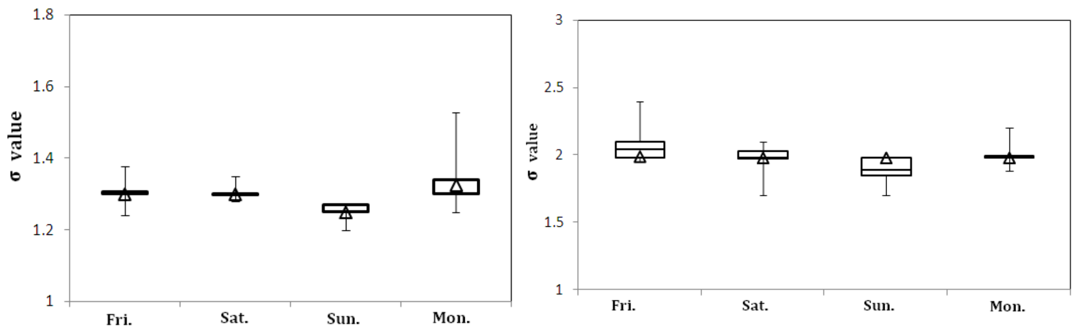
$\bar{D}_{p,i}$: nm; N_i: cm^{-3}.

Fig.9 and Fig.10 present parameters summary of the fitting curve results. Nuclei mode diameters were 21±1.8nm on Friday 17 June 2005, and 23±3.67nm on Monday 20 June 2005, median mode diameters were between 21~24nm monitored during the 4 days. Accumulation mode diameters were 77.3±15.2nm on Friday 17 June 2005 and 75.9±9.2nm on Monday 20 June 2005, the median accumulation mode diameters were between 74.5~87.5nm during the 4 days of monitoring. The median σ values (Geometric Standard Deviation) of nuclei mode of log-normal curves ranged in 1.27 to 1.31, and within the 0.25 to 0.75percentile value were 1.25~1.33. The median σ values of accumulation mode of log-normal curves ranged 1.89 to1.98; and within 0.25 to 0.75 percentile values were 1.85~2.1. Accordingly to the above size resolved PN EFs study, the accumulation mode and nuclei-mode log-normal PSD curves were processed from the emission data of diesel bus and CNG buses respectively.



Fitted mode diameter on Friday 17 June 2005   Fitted mode diameter on Monday 20 June 2005

Fig. 9 Mode diameters by fitting curve results



σ of nuclei mode log-normal curve σ of accumulation mode log-normal curve

Box-and-whisker plots indicate average (Thick horizontal line), Median (Triangle), first and third quartile (bottom and top edge of box, respectively), minimum and maximum (lower and upper extent of whiskers, respectively) daily nuclei mode diameter and accumulation mode diameter.

Fig.10 σ value results

Conclusion

By measuring the exposure level of tailpipe small particles for 4 consecutive days in a busway tunnel, we have sought to develop a methodology to characterize the log-normal UFPs size distributions of emissions from on-road diesel buses and CNG buses, as a result UFPs size and volume distributions would be determined by total particle number against a scaled diameter of the emitted particles.

The total particle number EFs (15~700nm) of the mixed fleet was 2.61E+14 p/veh.km. The total PN EFs found in this study shows no striking difference to the former real world measurements. By MLR method, total PN EFs of diesel buses and CNG buses were obtained as 3.96E+14 p/veh.km and 9.33E+13 p/veh.km correspondingly, distinctively diesel bus PN emission level was 4 times of that from CNG bus. For more information, particulate emission levels of 8 size ranges PN EFs according to the logarithmic average particle size were also derived as that. Diesel buses would emit particles mainly in 41-65 nm, 65-104 nm, 104-166 nm size section(accumulation mode), emission factors were 6.72E+13, 8.4E+13, 8.52E+13 p/veh.km. CNG buses would release smaller particles, mainly in the 15- 25 nm, and 25-41nm (nuclei-mode), emission factors were 5.84E+13, 2.69E+13 p/veh.km respectively.

PSD(Particle Size Distributions) of mixed traffic flow were decomposed by two log-normal fitting curves for each 30 minutes interval mean scans, all the mix fleet PSD emission can be well fitted by the summation of two log-normal distribution curves. The decomposed nuclei mode curves and accumulation curves were affirmed as PN emission curves of CNG buses and diesel buses respectively.

We also caught the signature of PSD curves base on 4 days of monitoring measurement data, the median mode diameters of diesel buses emission log-normal curve were between 74.5-87.5nm, correspondingly for CNG buses were between 21~24nm. The median σ of diesel and CNG buses PN log-normal emission curve is range in 1.27~1.31 and 1.89~1.98 separately.

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